STRUCTURAL CALCULATION OF DIVERSION TUNNEL LINING

[UPPER TRISHULI-1 HEP (216MW)]

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DOOSAN Doosan Heavy Industries & Construction

FOR APPROVAL

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Upper Trishuli-1 HEP (216MW)

Owner

NWEDC
NEPAL WATER AND ENERGY DEVELOPMENT CO. PVT.LTD.

Owner's Engineer

TRACTEBEL ENGIE

jade CONSULT

Contractor

DOOSAN Doosan Heavy Industries & Construction

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1 General

1.1 Background

Upper Trishuli-1 HEP is a project that uses the Trishuli River near Dunche and Haku. The construction site is located at rugged mountain between Tibet in China and the Himalaya Mountain which place 70 km away from capital, Kathmandu, towards the northwest. The headwork site is at 280m downstream from the confluence of Bhotekoshi and Trishuli rivers. The powerhouse site is 500m upward from Mailun Dobhan where Haku VDC is placed. The installed capacity of Upper Trishuli-1 HEP is 216 MW as a Run of River type. It is a year-round power plant which can generate about 1,533.4 GWh within a year.

The diversion tunnel is located on the right bank of Trishuli River. The cross section is horseshoe shape and 5.0m×5.0m size. The elevation of the inlet is at EL.1244.50m, and the elevation of outlet is at EL.1231.00m. The total length of diversion tunnel is 413.042m and longitudinal slope is 3.54%.

The profile of diversion tunnel is shown in Figure 1.1. The cross section is shown in Figure 1.2~1.5.

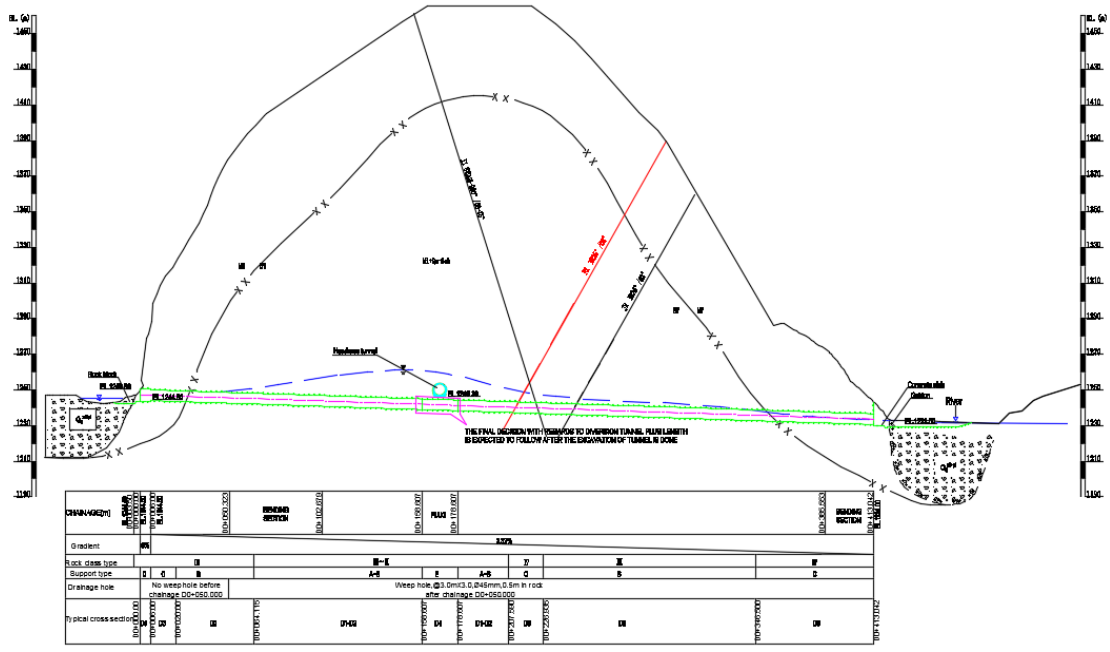

Figure 1.1 Profile section of diversion tunnel

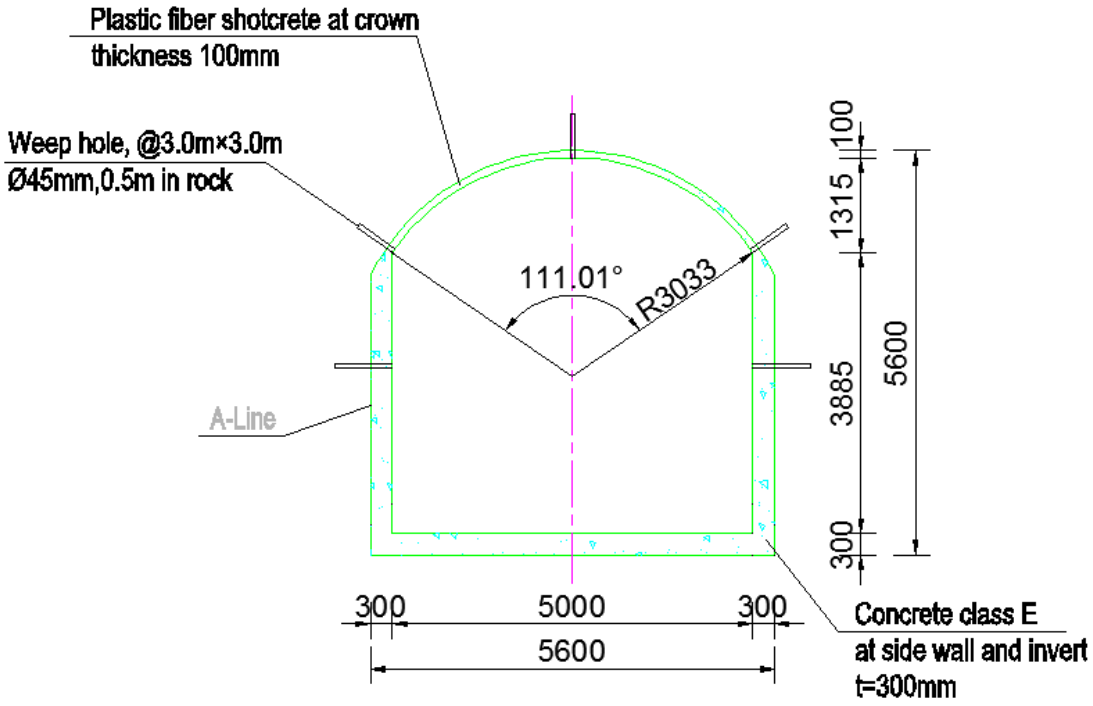

Figure 1.2 Typical section of diversion tunnel (Rock class II)

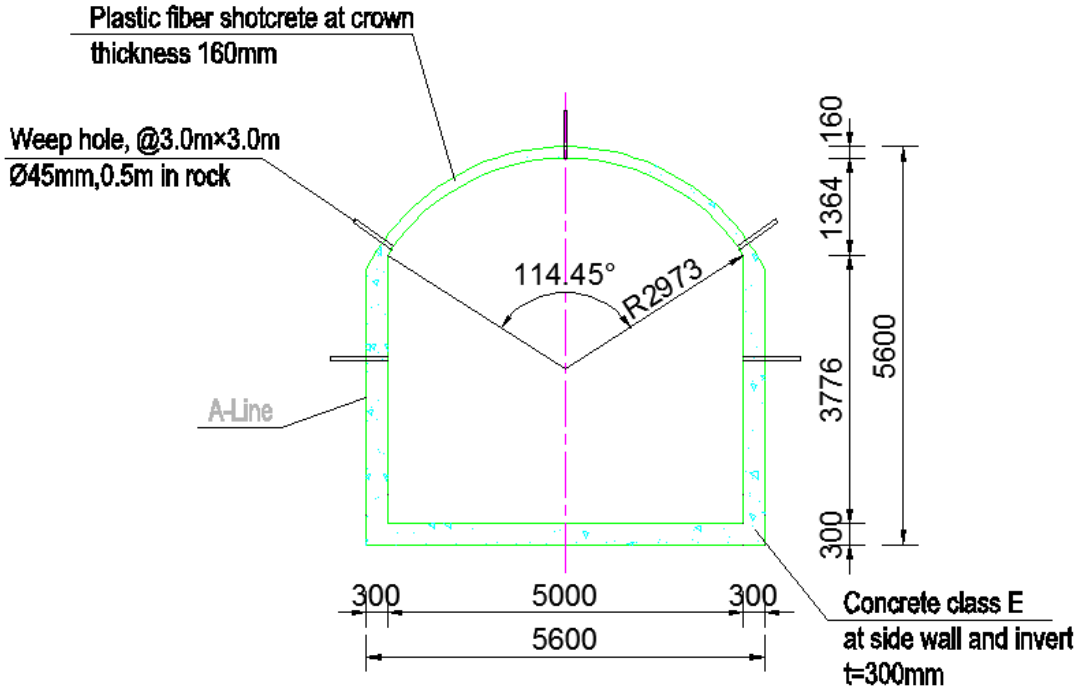

Figure 1.3 Typical section of diversion tunnel (Rock class III)

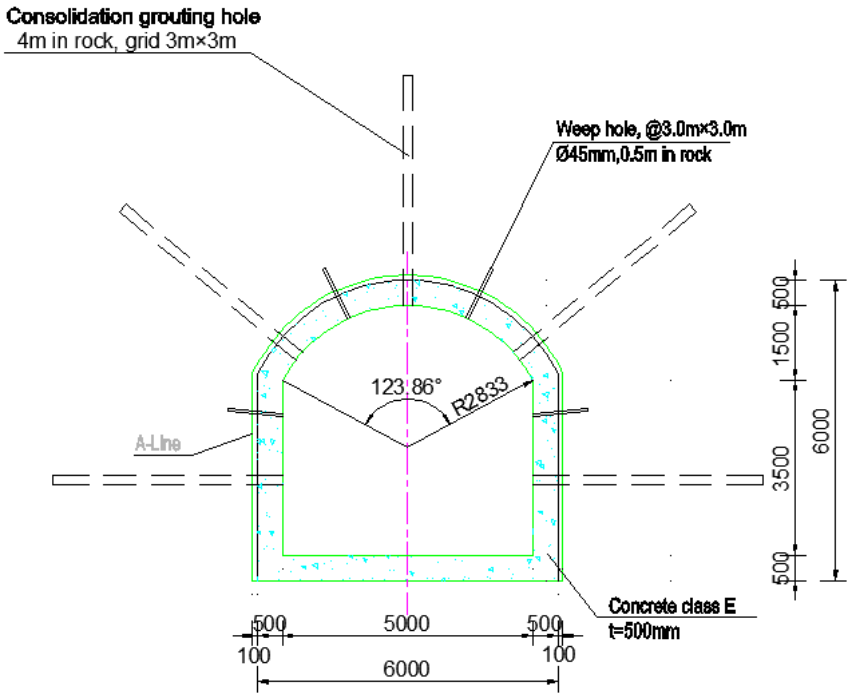

Figure 1.4 Typical section of diversion tunnel (Rock class IV)

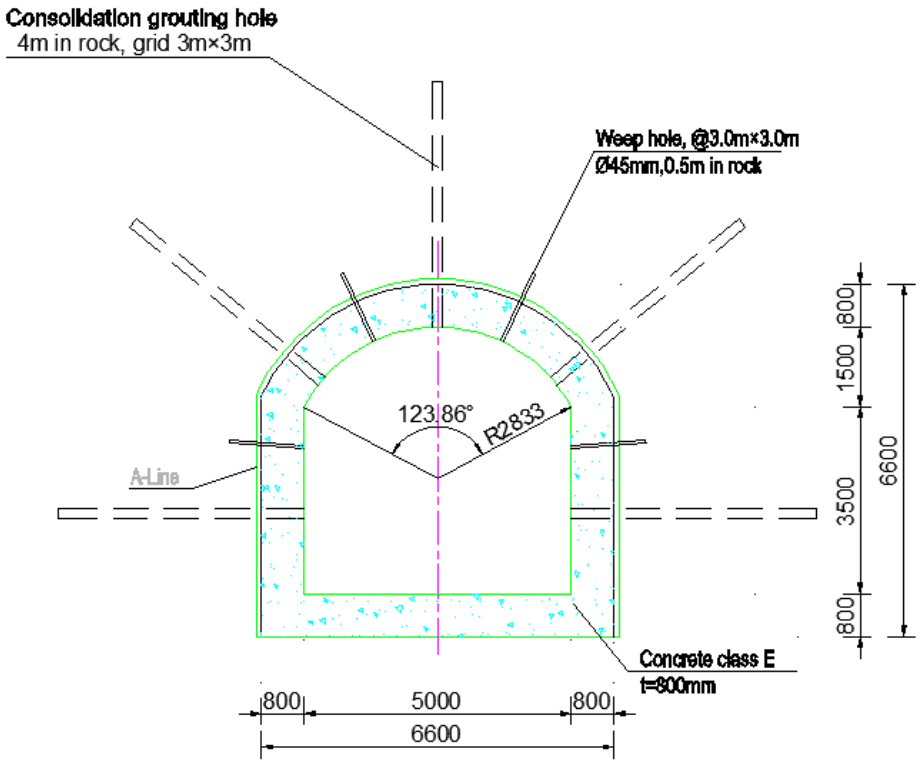

Figure 1.5 Typical section of diversion tunnel

(Intersection of headrace and diversion tunnel)

1.2 Design stage

This calculation is provided for detailed design stage.

1.3 Purpose and contents

Internal force of tunnel cross section is calculated with representative station numbers in line with arrangement of Diversion Tunnel, category of surrounding rock and pressure distribution of underground water, according to which reinforcements are configured to provide the basis for detail design of Diversion Tunnel. Please refer to Table 1.1 for table of station numbers at control section of Diversion Tunnel.

Table 1.1 Table of station numbers at control section of diversion tunnel

Section	Starting Station No.	Ending Station No.	Category of Surrounding Rock	Thickness of Lining (m)
1	D0+006.00	D0+020.000	III	0.5
2	D0+020.000	D0+064.115	III	0.3
3	D0+064.115	D0+158.607	II-III	0.3
4*	D0+158.607	D0+178.607	II-III	0.8
5	D0+178.607	D0+207.590	II-III	0.3
6	D0+207.590	D0+226.935	IV	0.5
7	D0+226.935	D0+346.500	III	0.3
8	D0+346.500	D0+413.042	IV	0.5

(Note: Section 4* is intersection of headrace and diversion tunnel)

2 Reference Document

2.1 Rules and regulations

(1) Tunnels and Shafts in Rock (EM 1110-2-2901);

(2) Strength Design for Reinforced Concrete of Hydraulic Structure (EM1110-2-2104);

(3) Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (ACI

318-11);

2.2 Technical documents

(1) Outline Drawing of Diversion Tunnel (UT1-C-010-CVL-DG-42004)

3 Calculation Process

3.1 Material characteristics and calculation parameters

(1) Concrete

a) Class E (Cylinder compressive strength is 24MPa)

Volume weight of reinforced concrete: 25.0kN/m ^{3};

b) Elastic modulus and Poisson's ratio is shown in Table 3.1.

Table 3.1 Elastic modulus and Poisson's ratio

Elastic Modulus E_c (MPa)	Poisson's Ratio
2.3×10^4	0.2

(2) Reinforcement

a) Yield strength of deformed bar: 500MPa;

b) Yield strength of round bar: 280MPa;

c) Elastic modulus: 200,000MPa;

(3) Physical and mechanical parameters of rocks

Table 3.2 Mechanical parameter of diversion tunnel surrounding rock

Class of surrounding rock	Saturated compressive strength	Elastic modulus	Poisson ratio	Rock mass/rock mass shear (shearing) strength	
	(MPa)	(GPa)		Φ (°)	c´ (MPa)
II	13	20.5	0.25	48	2.5
III	4.2	7.5	0.27	45	1.0
IV	1.9	2.3	0.30	35	0.5

(4) water level in work condition

When the water flow through the diversion tunnel in 5-year flood season, the upstream water level is EL.1260.5m.

When the tunnel is building, the upstream water level is taken as zero, the tunnel is empty.

When the Plugging is building, the river flow will be discharged through the orifices of weir/dam, the upstream water level of weir/dam is 1247.6m, and the water level of diversion tunnel inlet is 1250.17m back calculated from weir/dam location.

3.2 Calculation principle and method

The calculation takes the method of bedded-beam-spring recommended in Chapter 9 of EM 1110-2-2901 Tunnels and Shafts in Rock that simulates lining section with SAP2000 middle beam element and the arc length corresponding to every 5 °central angle as the unit length and simulates interaction between lining and surrounding rock by applying normal and tangential spring gap elements to nodes. Reinforcements of lining section are configured according to result of internal force calculation. Figure 3.1 is illustration of concrete lining model.

Stiffness of spring elements is calculated by the following formulas:

For normal stiffness

$$k_r = E_r b\theta/(1+\nu_r)$$

For tangential stiffness

$$k_t = k_r G / E_r = 0.5k_r/(1+\nu_r)$$

Wherein:

k_r and k_t: Normal and tangential stiffness of springs; kN/m

E_r: Elastic modulus of surrounding rock; kPa,shown in the Table 3.2.

θ: Central angle of beam element; radian

b: Calculative width; m

G_r: Shear modulus of surrounding rock; kPa:

ν_r: Poisson's ratio of surrounding rock

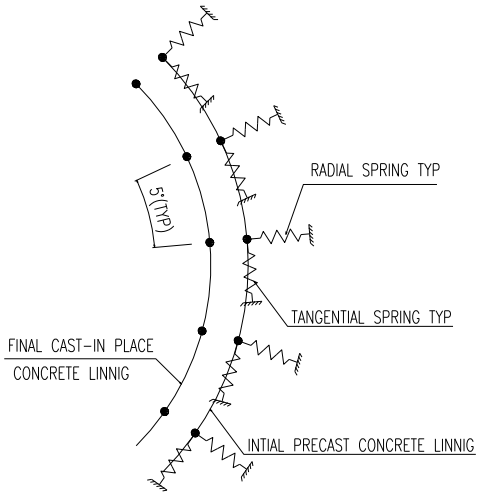

Figure 3.1 Illustration of concrete lining model

Gap Property

For each deformational degree of freedom you may specify independent gap ("compression-only") properties. See Figure 56 (page 258).

258 Gap Property

Chapter XV The Link/Support Element—Advanced

All internal deformations are independent. The opening or closing of a gap for one deformation does not affect the behavior of the other deformations.

If you do not specify nonlinear properties for a degree of freedom, that degree of freedom is linear using the effective stiffness, which may be zero.

The nonlinear force-deformation relationship is given by:

$$f = \begin{cases} \mathbf{k}\,(d + \mathbf{open}) & \text{if } d + \mathbf{open} < 0 \\ 0 & \text{otherwise} \end{cases}$$

where **k** is the spring constant, and **open** is the initial gap opening, which must be zero or positive.

The gap elements (springs) is installed in the all circumference (360 °angel). The gap elements are also used for external pressure load cases. When the lining is bearing internal pressure, the gap element is equal to spring. In negative case, for example, external pressure case, it will separate lining from surrounding rock surface.

The method is regarding SAP2000 program advance instruction book.

According to formulas in section 3.2, normal stiffness and tangential stiffness of rock class II,

rock class III and rock class IV are as listed in Table 3.3.

Table 3.3 Normal and tangential stiffness of surrounding rock (unit length)

Rock class	Normal Stiffness k_r (calculated with elastic modulus) (kN/m)	Tangential Stiffness k_t (calculated with elastic modulus) (kN/m)
Rock class II	5857142.9	2342857.1
Rock class III	2109111.4	830358.8
Rock class IV	570719.6	219507.5

3.3 Combination of working conditions and calculation of loads

3.3.1 Combination of working conditions

According to table 9-1, EM1110-2-2901, loads acted on the lining include lining self-weight, internal water pressure, external water pressure, surrounding rock load, etc.

Additionally, it is reminded that according to the U.S.A.C.E. Manual EM 1110-2-2901, paragraph 9.4, item f: “In most cases, the rock is stabilized at the time the concrete lining is placed, and the lining will accept loads only from water pressure (internal, external, or both)." So the surrounding rock load is taken into account in rock class IV.

Loads and combination of working conditions are as stated in Table 3.4 and load factor under respective working condition is as listed in Table 3.5.

Table 3.4 Operation conditions and relevant loads

No.	Working Condition of Calculation	Self-weight	Internal Water Pressure	External Water Pressure	Surrounding rock
CASE1	Normal operation period	√	√		
CASE2	Plugging period	√		√	√
CASE3	Diversion tunnel construction period	√		√	√

Table 3.5 Load factor under every working condition

No.	Working Condition	Self-weight	Internal	External	Surrounding

	of Calculation		Water Pressure	Water Pressure	rock
CASE1	Normal operation period	1.3	1.4		
CASE2	Plugging period	1.1		1.4	1.4
CASE3	Diversion tunnel construction period	1.1		1.4	1.4

3.3.2 Calculation of Loads

(1) Internal and external water pressure

The water level is 1260.5m in 5-year flood season. The water level is 1250.17m in Plugging period. In Diversion tunnel construction period, the tunnel is empty, the internal water pressure is zero.

(2) External water pressure and reduction factor of external water pressure

Regarding to《DESIGN OF CONCRETE LINENGS OF PRESSURE TUNNELS AND SHAFTS FOR EXTERNAL WATER PRESSURE》， the consolidation grouting reinforcement effect for surrounding rockmass is not taken into account, the external water pressure reduced factor in category III and category IV can be calculated by following equation:

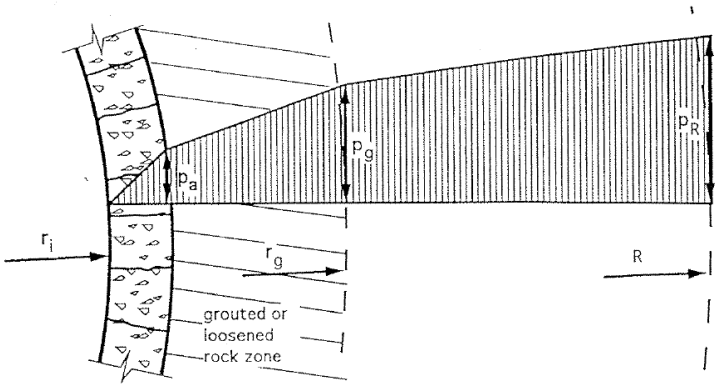

Figure 3.2 seepage flow from the rock mass through cracked concrete lining into the tunnel

a. the water inflow from the rockmass per unit length of tunnel

$$q_r = \frac{2\pi k_r \left(b - p_g / (\rho_w \cdot g) \right)}{\ln \left[b / r_g \cdot \left(1 + \sqrt{\left(1 - r_g^2 / b^2 \right)} \right) \right]} = C_1 \left(b - p_g / (\rho_w \cdot g) \right) \tag{3-1}$$

b. the seepage flow through grouted and loosened rock zone per unit length of tunnel

$$q_g = \frac{2\pi k_g \left((p_g - p_a) / (\rho_w \cdot g) \right)}{\ln \left[r_g / r_a \right]} = C_3 (p_g - p_a) / (\rho_w \cdot g) \tag{3-2}$$

c. the seepage flow through across the concrete lining per unit length of tunnel

（1）the seepage flow through the uncracked concrete between the cracks is given by:

$$q_{c1} = \frac{2\pi k_c p_a / (\rho_w \cdot g)}{\ln \left[r_a / r_i \right]} = C_{41} p_a / (\rho_w \cdot g) \tag{3-3}$$

（2）the water conductivity of the radial cracks is given by following equation:

$$q_{c2} = \frac{2\pi r_i (2a_1)^3 \cdot g \cdot p_a / (\rho_w \cdot g)}{12\nu_w \cdot (r_a - r_i) d} = C_{42} p_a / (\rho_w \cdot g) \tag{3-4}$$

（3）the water conductivity of the longitudinal cracks is given by following equation:

$$q_{c3} = \frac{n \cdot (2a_2)^3 \cdot g \cdot p_a / (\rho_w \cdot g)}{12\nu_w \cdot (r_a - r_i)} = C_{42} p_a / (\rho_w \cdot g) \tag{3-5}$$

the total seepage flow through across the concrete lining per unit length of tunnel:

$$q_c = q_{c1} + q_{c2} + q_{c3} = (C_{41} + C_{42} + C_{43}) \cdot p_a / \rho_w = C_4 \cdot p_a / \rho_w \tag{3-6}$$

d.the external water pressure

Because of $q_r = q_g = q_c$, the external water pressure is calculation by following equation:

$$p_a / (\rho_w \cdot g) = \frac{C_{1(2)} b}{\left((C_3 + C_4) / C_3 \right) (C_{1(2)} + C_3) - C_3} \tag{3-7}$$

Reduction factor of external water pressure can be calculated by following equation:

$$\beta = \frac{p_a}{b} \tag{3-8}$$

Where,

$(2a_1)$ =average width of radial cracks

$(2a_2)$ =average width of longitudinal cracks

b =depth of the tunnel below groundwater level

E =modulus of elasticity

r =subscript for rock

c =subscript for concrete

g =subscript for grouted or loosened rock zone

g =acceleration due to gravity

k_c =permeability of uncracked concrete

k_r =permeability of rock mass

n =number of longitudinal cracked

p_a =water pressure on the outer side of the concrete lining

p_g = water pressure on the outer side of grouted or loosened rock zone

r_i =internal radius of lining

r_a =externa; radius of lining

r_g =radius of grouted or loosened rock zone

R =external radius of the rock zone affected by the seepage

q =water inflow per unit length of tunnel

v =Poisson ratio（subscripts as E）

v_w =kinematic viscosity of water

ρ_w = density of water

In according to 9-1. Selection of a Permanent Lining，paragraph f，EM2901，the factor Kw with weep hole is taken as 0.25，the factor is taken as 1 without weep hole. So the total external pressure Pe is calculated by the formula below:

$$Pe=b\times\beta\times Kw$$

Table 3.6 Calculation of external water pressure

Rock class	Permeability Coefficient (m/s)	Lining Thickness(m)	depth of the tunnel below groundwater level b(m)	External Water Reduction Factorβ	Factor Kw for weep hole
II	1e-8	invert: 0.3m wall: 0.3m	21.9(for case3)	0.016	0.25
III	1e-7	invert: 0.3m wall: 0.3m	7.63(for case2)	0.14	1
IV	1e-6	0.5m	17.4(for case2)	0.34	1
III (Intersection of headrace and diversion tunnel)	1e-7	0.8m	16.6(for case3)	1	1

(3) Surrounding rock pressure

a. According to EM1110-2-2901, vertical rock pressure $q_{vk} = S_y \gamma_r H_A$, $S_y = 0.3$; horizontal rock pressure $q_{hk} = S_x \gamma_r H_A$, $S_x = 0.15$; of which H_A is excavation height of the tunnel, γ_r is surrounding rock weight, S_y is vertical rock pressure coefficient, S_x is horizontal rock pressure coefficient.

for rock class IV:

Vertical rock pressure q_{vk}:

$$q_{vk} = S_y \gamma_r H_A = 0.3 \times 25.5 \times 5.5 = 42.0 kN/m$$

Horizontal rock pressure q_{hk}:

$$q_{hk} = S_x \gamma_r H_A = 0.15 \times 25.5 \times 5.5 = 21.0 kN/m$$

b. Intersection of headrace and diversion tunnel

Vertical rock pressure is calculated according to average rock thickness between headrace and diversion tunnel, which is 3m.

Vertical rock pressure q_{vk}:

$$q_{vk} = \gamma_r H_A = 25.5 \times 3 = 76.5 kN/m$$

3.3.3 Calculation Model

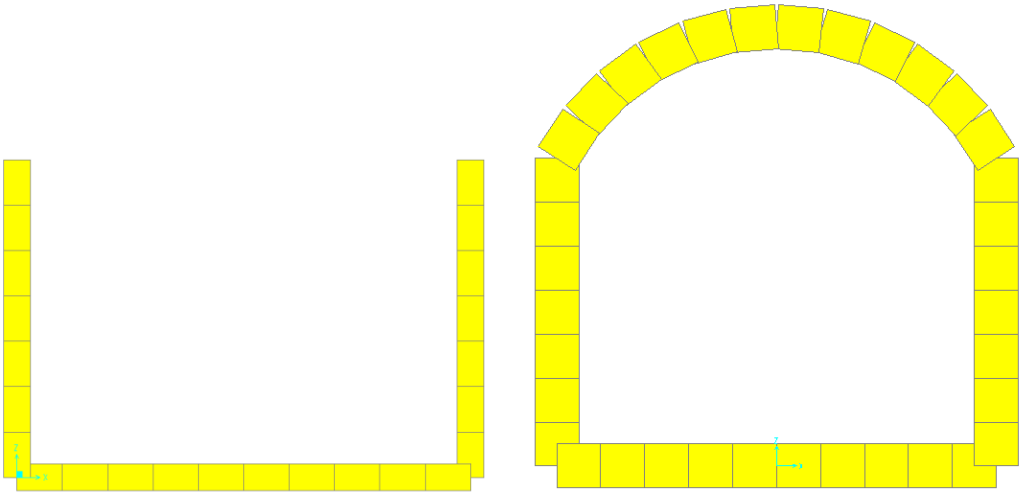

Figure 3.3 Calculation model of concrete lining of rock class III and IV

4 Calculation Result

All internal water pressures which induce a load into the tunnel lining are transferred into the surrounding rock and are not critical, so the result of external water pressures are listed as follows:

4.1 Figure of internal force

4.1.1 Figure of internal forces of concrete lining (Rock class II)

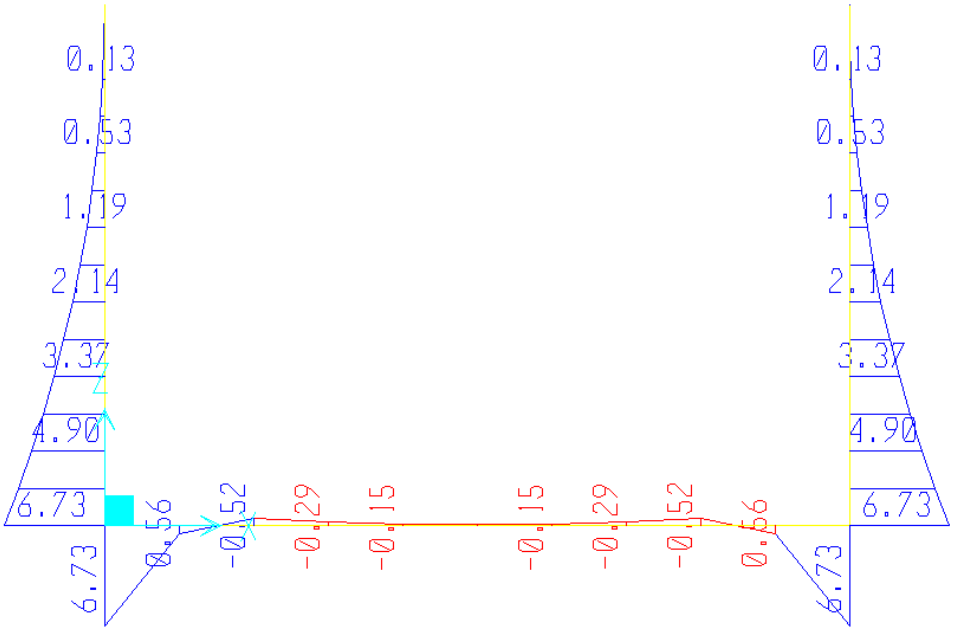

Figure 4.1 Figure of Bending Moment at Concrete Lining Section (CASE3)

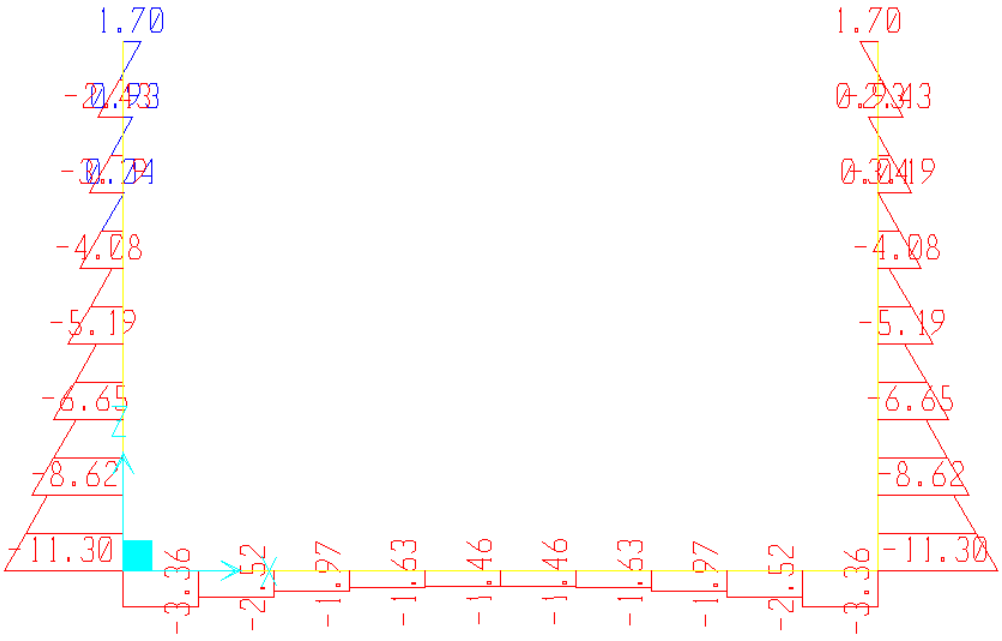

Figure 4.2 Figure of Axial Force at Concrete Lining Section (CASE3)

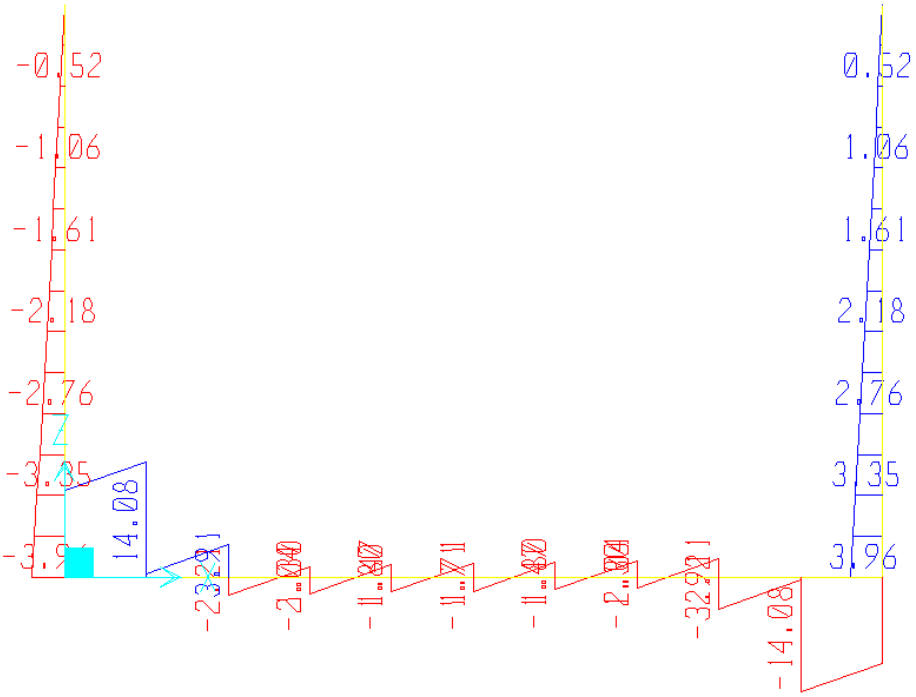

Figure 4.3 Figure of Shear Force at Concrete Lining Section (CASE3)

4.1.2 Figure of internal forces of concrete lining (Rock class III)

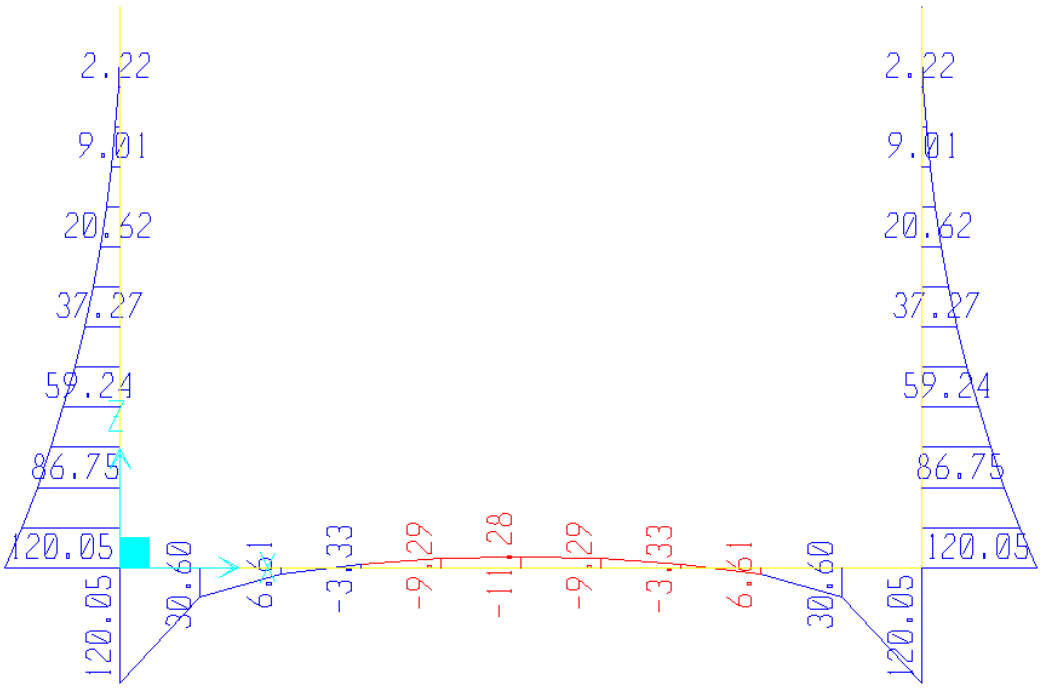

Figure 4.4 Figure of Bending Moment at Concrete Lining Section (CASE2)

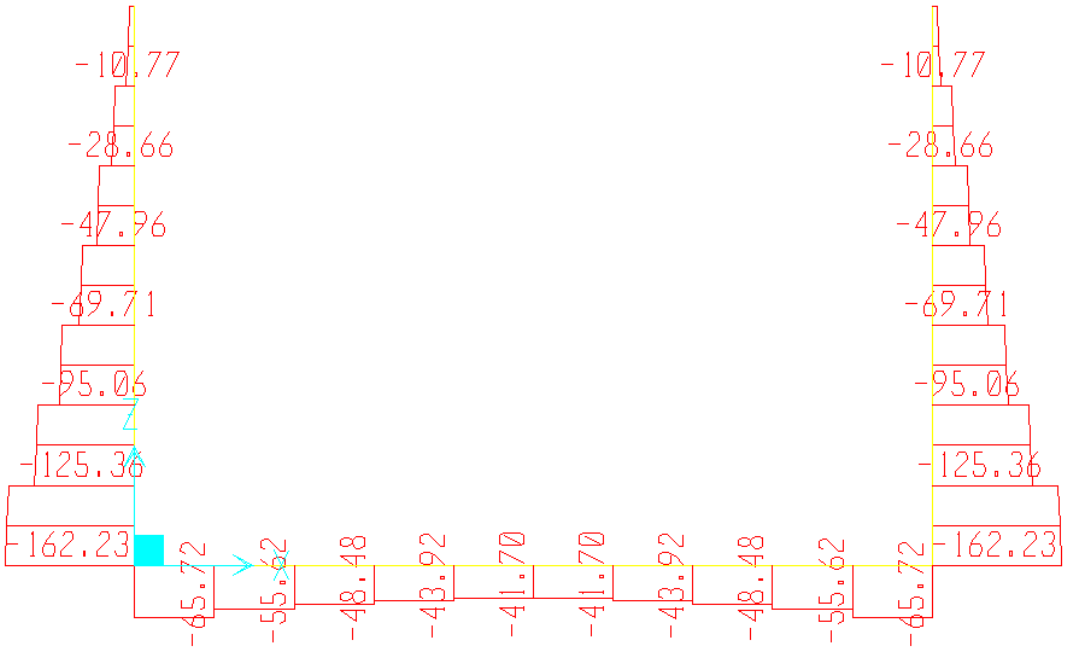

Figure 4.5 Figure of Axial Force at Concrete Lining Section (CASE2)

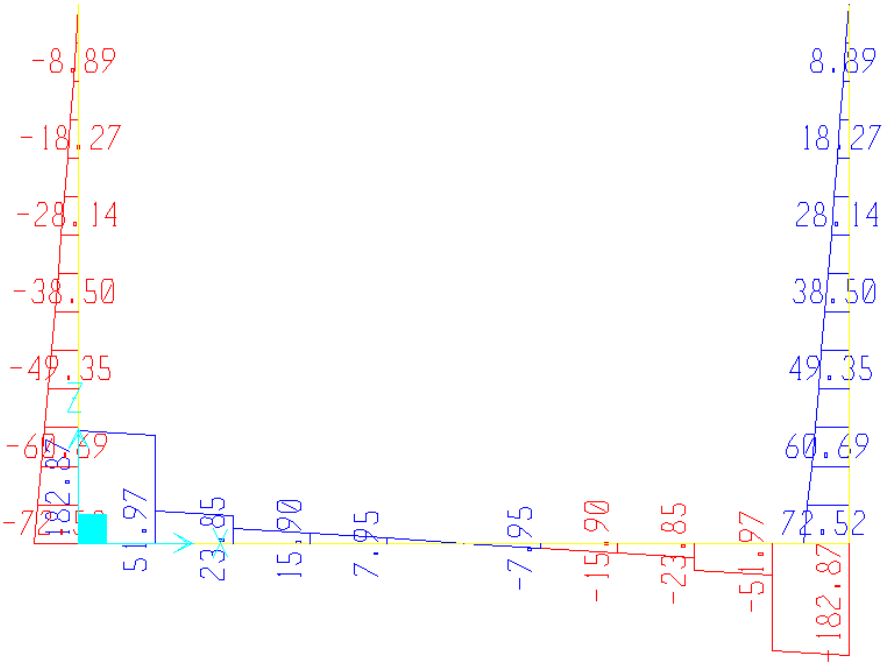

Figure 4.6 Figure of Shear Force at Concrete Lining Section (CASE2)

4.1.3 Figure of internal forces of concrete lining (Rock class IV)

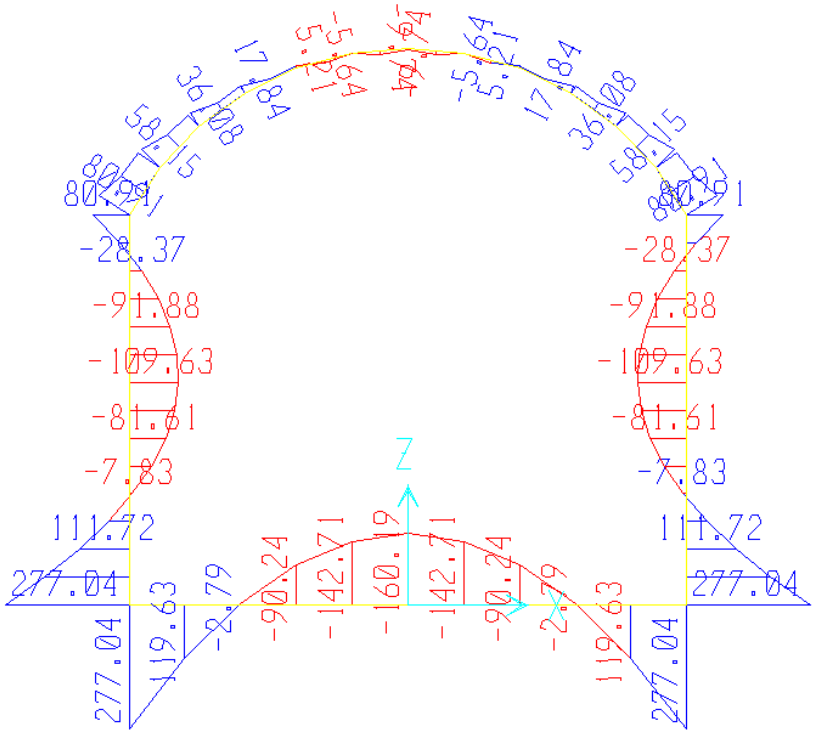

Figure 4.7 Figure of Bending Moment at Concrete Lining Section (CASE2)

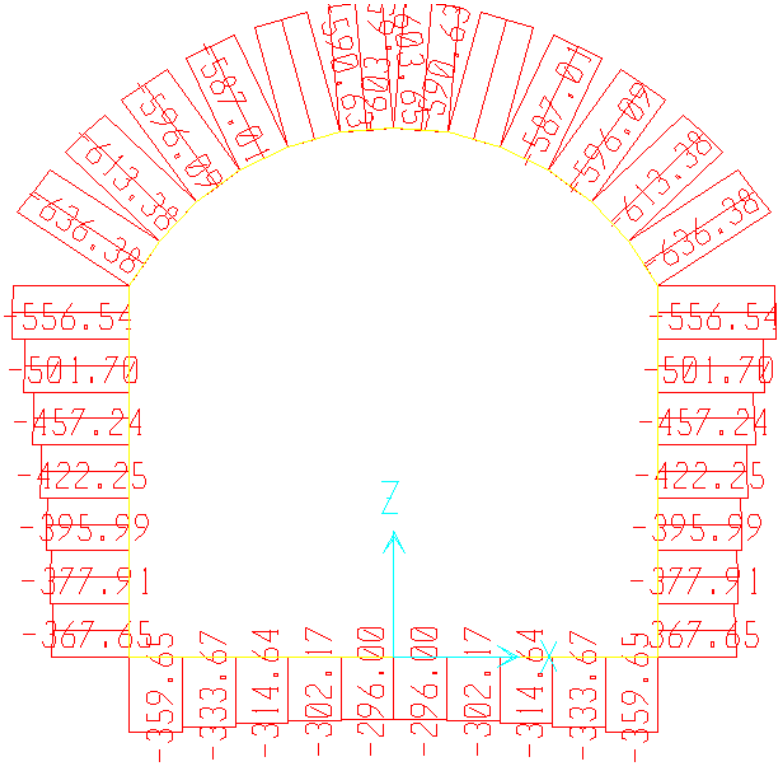

Figure 4.8 Figure of Axial Force at Concrete Lining Section (CASE2)

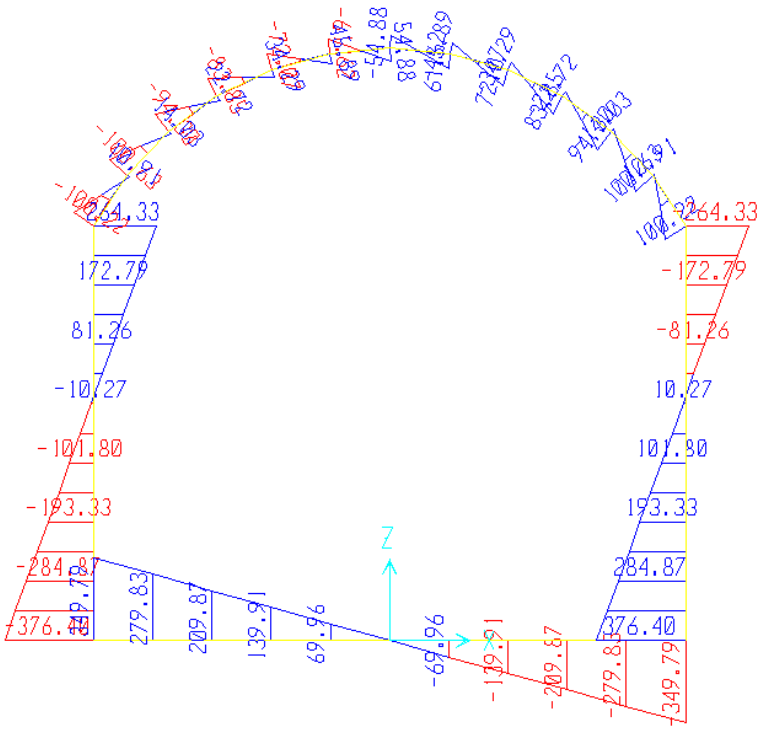

Figure 4.9 Figure of Shear Force at Concrete Lining Section (CASE2)

4.1.4 Figure of internal forces of concrete lining (Intersection of headrace and diversion tunnel)

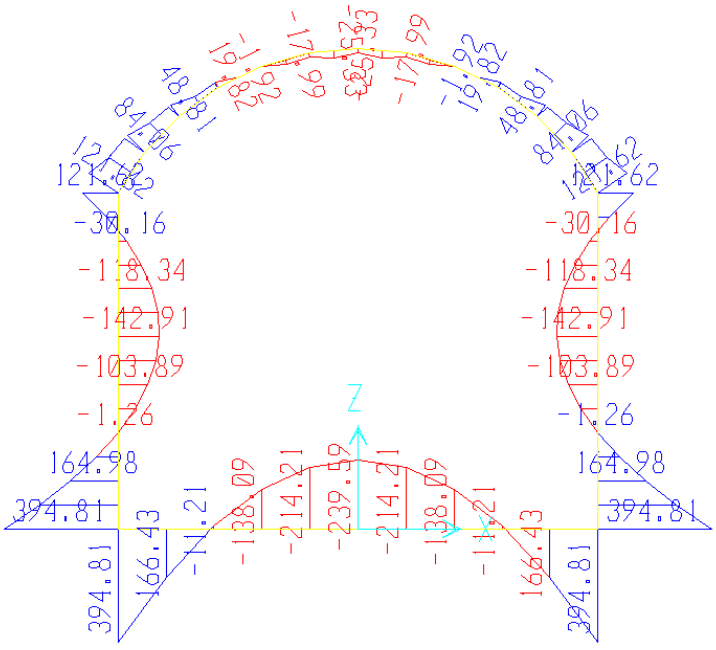

Figure 4.10 Figure of Bending Moment at Concrete Lining Section (CASE3)

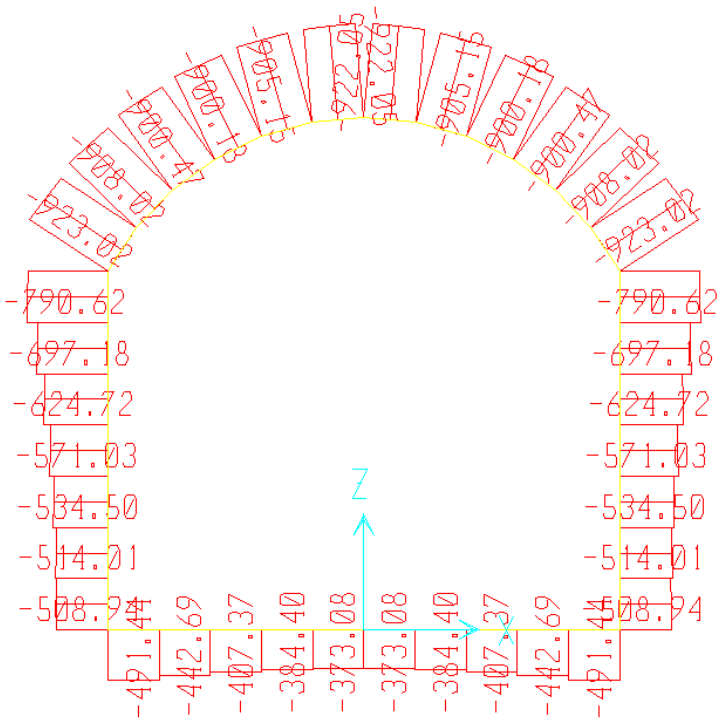

Figure 4.11 Figure of Axial Force at Concrete Lining Section (CASE3)

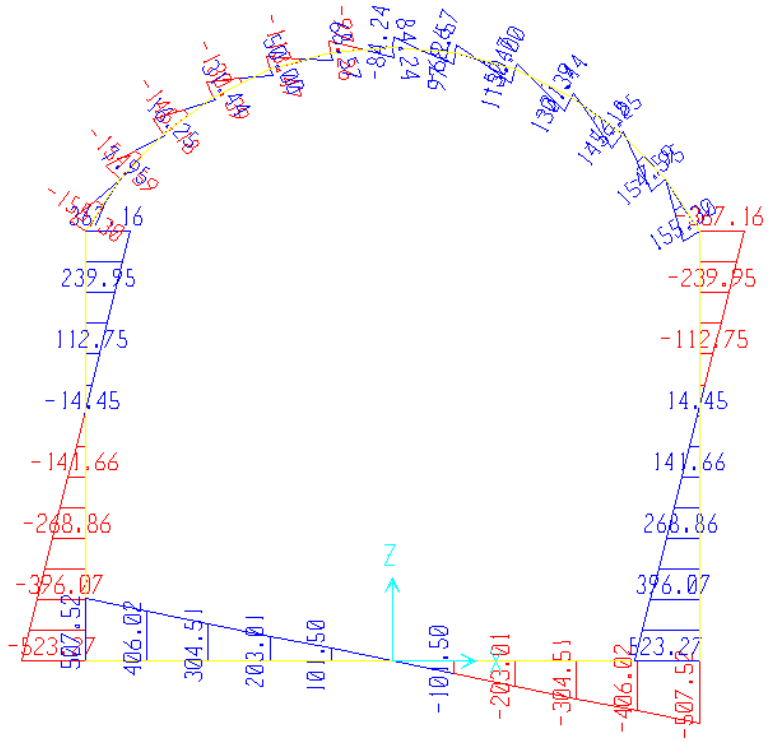

Figure 4.12 Figure of Shear Force at Concrete Lining Section (CASE3)

4.2 Table of internal force

Table 4.1 Result of internal force calculation

Rock class	Part	M(kN.m)	P(kN)	V(kN)
II(CASE3)	wall	6.73	-11.3	3.96
	invert	6.73	-3.36	14.08
III (CASE2)	wall	120.05	-162.23	72.52
	invert	120.05	-65.72	182.87
IV(CASE2)	crown	80.91	-636.38	100.2
	wall	277.04	-367.65	376.4
	invert	277.04	-359.65	349.7
Intersection of headrace and diversion tunnel(CASE3)	crown	121.61	-923.0	155.3
	wall	394.81	-508.94	523.27
	invert	394.81	-491.44	507.5

(Note: in the table, M Table refers to bending moment, V Table shear force and P Table axial force. The axial force is negative when compressed.)

5 Conclusions

According to the calculation results of Bending Moment, Axial Force and Shear Force. Reinforcement is follow the standard EM1110-2-2104 and ACI 318-11. The Reinforcement Sketch refer to figure 5.1~5.4. Dimensions are in meter, and diameters and spacing of rebar are in millimeter.

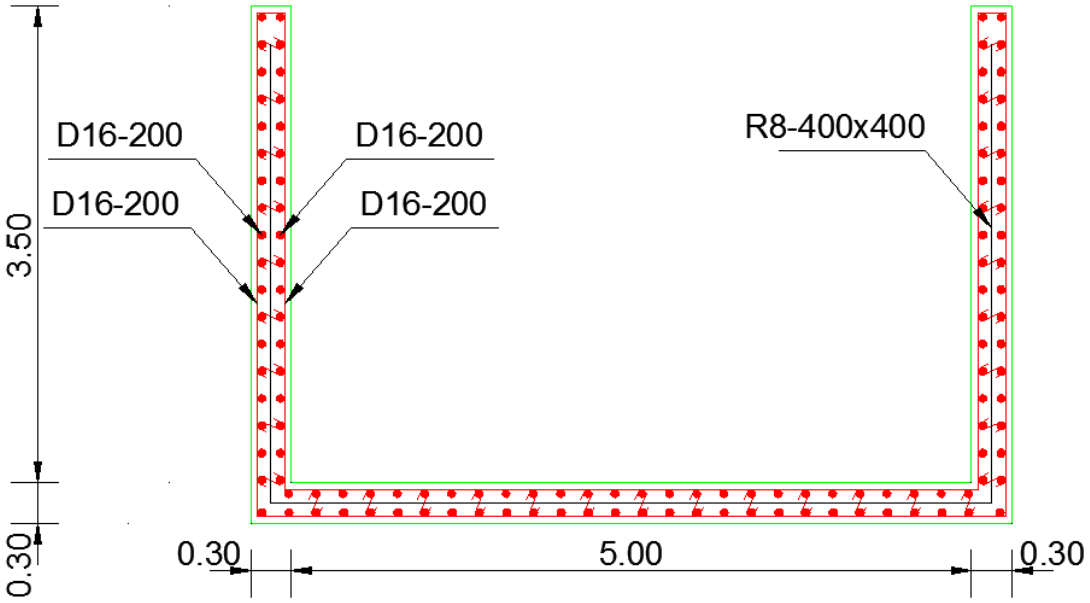

Figure 5.1 Typical cross section (Rock class II)

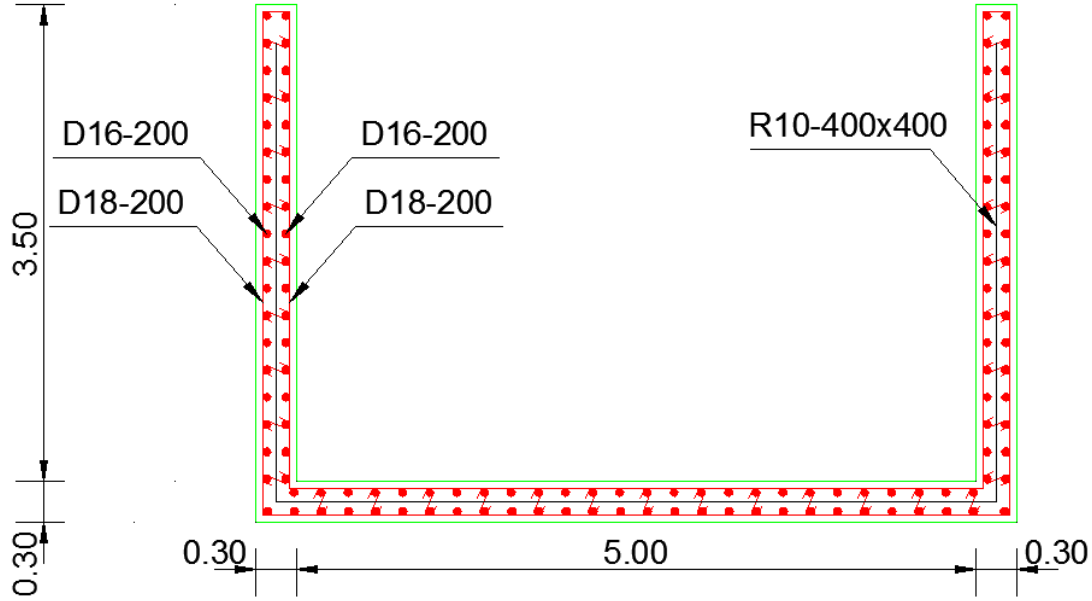

Figure 5.2 Typical cross section (Rock class III)

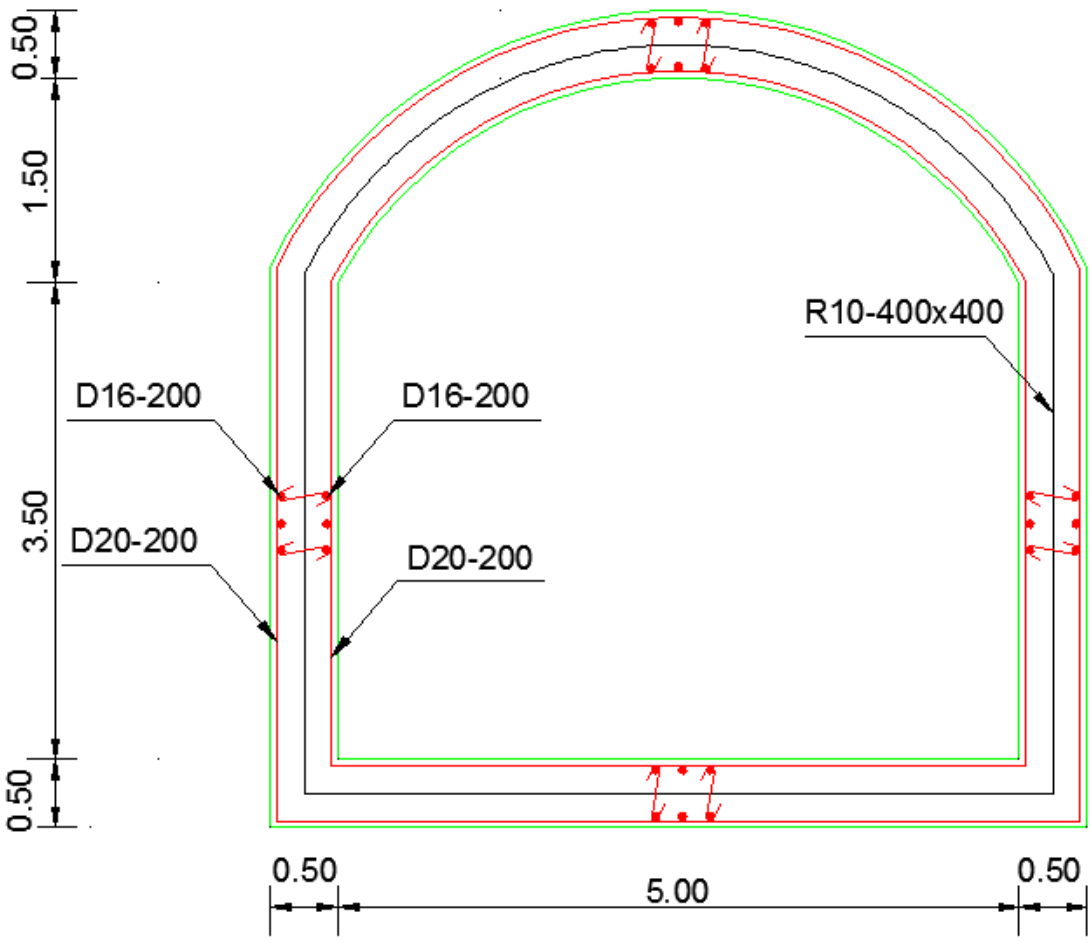

Figure 5.3 Typical cross section (Rock class IV)

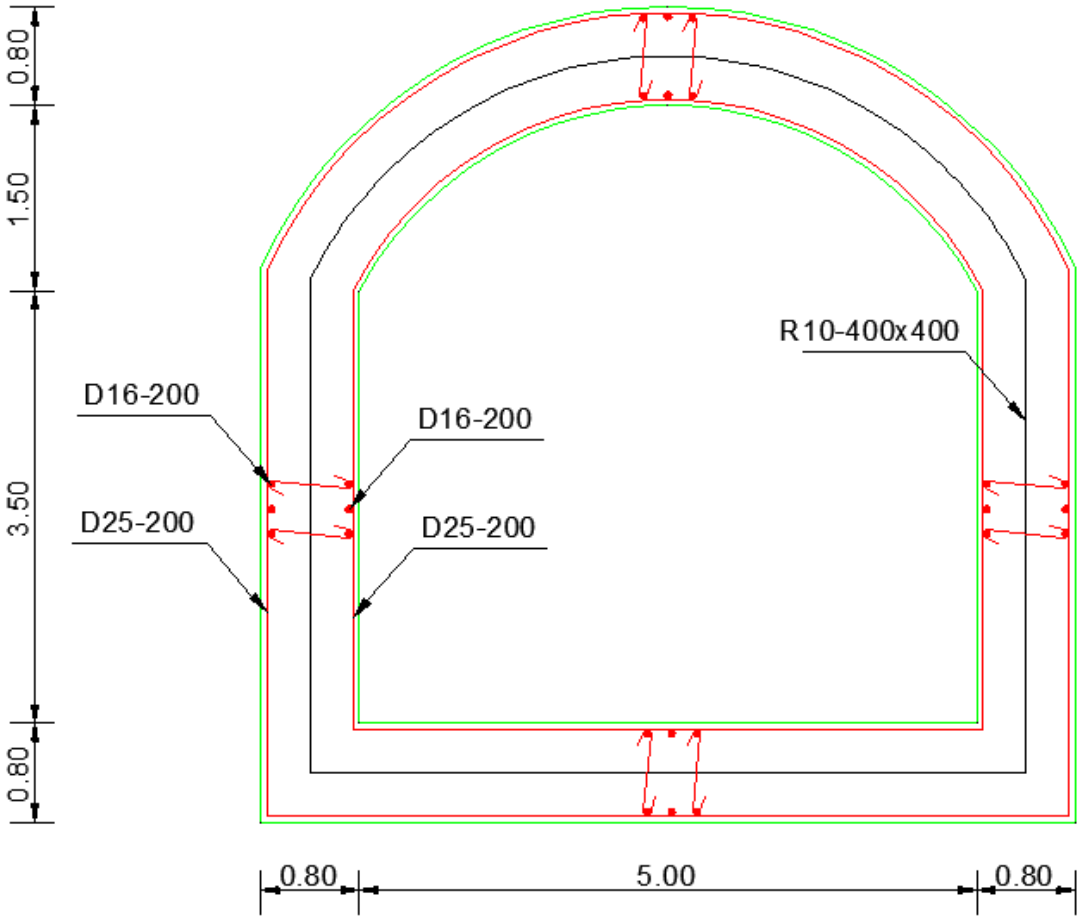

Figure 5.4 Typical cross section (Intersection of headrace and diversion tunnel)